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Hardesty, John F.

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HIGH SPEED PHOTOGRAPHIC INVESTIGATION OF THE FIRST BUBBLE PERIOD CREATED BY AN UNDERWATER EXPLOSION

JOHN F. HARDESTY

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UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

HIGH SPEED PHOTOGRAPHIC INVESTIGATION

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by

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Submitted in partial fulfillment of
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IN
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ABSTRACT

A relatively safe and inexpensive method was developed for the investigation of the oscillating bubble caused by the hot gases from an underwater explosion. High speed photography was employed to record the pulsations of the bubble caused by the detonation of decigram center-detonated spherical charges of P.E.T.N. Timing marks on the film were used to record the time interval or period of each oscillation. A description of the equipment constructed and used in the investigation is included in the body of the report.

Calculations were carried out using the bubble period data and a semi-empirical equation with a rational basis to arrive at the relative underwater explosive strength of P.E.T.N. and T.N.T. Results obtained and recommendations for future work are offered in the last part of the report.

Photographs of the entire sequence of events of an underwater explosion from detonation to the collapse of the second bubble are included as a appendix to this report.

ACKNOWLEDGMENT

The writer wishes to express his appreciation to Professors G. F. Kinney, J. E. Sinclair, J. W. Wilson, J. M. Bouldry, M. L. Wilcox, J. R. Borsting and L. E. Kinsler of the U.S. Naval Postgraduate School and J. Pearson, L. N. Cosner, and R. Gallup of the U.S. Naval Ordnance Test Station, China Lake, California, for assistance, advice and encouragement during the course of this project.

Further, the technical support and assistance of the Postgraduate School Machine Shop, W. J. Morgan PH2 of the Photographic Laboratory, P. Savo of the Metallurgy and Chemistry Department, and R. K. Overlock ET1 of the Electronics Department were invaluable in the successful completion of this investigation.

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LIST OF ILLUSTRATIONS

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TABLE OF SYMBOLS

E_{max}	- (joules)	Maximum energy released from a condenser
C	- (farads)	Capacitance of a condenser
V	- (volts)	Voltage across a condenser
μ	- (grams)	Mean or average mass of P.E.T.N.
T_n	- (seconds)	nth period of oscillation
Z_n	- (feet of water)	Hydrostatic pressure on charge
Q	- (kilocalories per gram)	Detonation energy
W	- (grams)	Mass of explosive
r_n	- (dimensionless)	Fraction of detonation energy which remains for the nth oscillation of period T_n

1. Introduction.

The purpose of this experiment was to investigate the underwater explosive strength of explosives on a laboratory scale. This was to be accomplished by bubble period measurements taken from high speed photographic film.

The usual experimental method of comparing the relative strength of different explosives is to detonate a known amount of a standard explosive in a testing device (Trauzel Block or Ballistic Mortar), and then detonate the same amount of test explosive in the same testing device. The relative strength of the test explosive compared to the standard can then be obtained by comparing the work done by the two explosives. The standard explosive used in the United States is T.N.T. (Trinitrotoluene). Another experimental method developed in the last 20 years is to measure the bubble period either by pressure measurements or photography of a standard explosive (again T.N.T.), and then compare this to the bubble period of test explosives. The bubble period is the time interval between successive minima in the bubble radius, and it is a measure of the explosive strength of an explosive. The bubble is formed by the gaseous products of an underwater explosion and oscillates until all the energy of the explosion is finally dissipated. The bubble is not to be confused with the shock wave which is the first event that takes place after detonation. The shock wave is responsible for the dissipation of approximately 50% of the energy of explosion as explained in reference (1).

This investigation deals with the relative underwater explosive strength of P.E.T.N. (Penta-Erytritol Tetranitrate) and T.N.T.. The equation used for this collation was originally derived by H. F.

Willis. Reference (2). The actual equation used with the correct constant is taken from reference (1).

The photographic techniques necessary for the successful completion of this investigation were acquired at N.C.T.S. (U.S. Naval Ordnance Test Station, China Lake, California). Some of the most successful photographic work in this field was accomplished by Lieutenant D. C. Campbell, U.S.N.R., at the David W. Taylor Model Basin. References (3) and (4).

The field of underwater explosions is a wide one. Most of the available literature is in the form of naval reports. The two primary sources available in the open literature are references (1) and (5). An excellent history of the developments of underwater explosion research is contained in reference (6).

2. Experimental Procedure and Apparatus.

General.

The physical arrangement of apparatus used to conduct this investigation is shown in figures (1), (2), (3), (4), (5), and (6).

Small bare spherical charges were suspended in a tank of water by the wires used to detonate the charge. The charge was detonated by closing a switch in the firing circuit. Motion pictures of the bubble that formed from the explosion of the charge were taken with a high-speed camera. A pulse generator triggered a neon lamp built into the camera which put timing marks on the film. The film was analyzed after development to obtain the time from detonation to the collapse of the first bubble. This time interval is called the First Bubble Period.

The Explosion Tank.

The tank that held the water was constructed of 3/8 inch steel plate welded at the edges. It was 36 inches high with a base 30 by 30 inches. Fresh tap water was put into the tank to a depth of 30 inches. The tank had four glass ports, one on each side, which were taken from obsolete B-29 aircraft. They were constructed of two layers of plate glass. The glass next to the water was 3/8 inch thick, the exterior plate of glass was 1/4 inch thick, and there was a 1/4 inch insulating air space between them. The air space was vented to the atmosphere by a small hole through the exterior plate of glass. The port was made into an integral unit by a thin metal band around its periphery. Holes were cut in the sides of the tank to receive the integral parts. Each port was secured to the tank by 26 screws with the head of the screw on the outside. This method was used to insure any shock from the explosion would be felt by the exterior plate of glass rather than

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the interior one. The method proved fortunate. Even though the outside plate of glass was cracked severely from repeated shocks, the inside plate showed no damage, as may be seen in figure (1).

The front port was left transparent to give the camera an unobscured view of the bubble as it formed and collapsed. The two side ports were left transparent to allow as much illumination as possible to impinge on the bubble. The back port was rendered translucent by spraying a commercially obtained product called "Pactra Glass Frosting" on the outside. This allowed the bubble to be viewed by the camera in silhouette.

The inside of the tank was painted with a glossy white paint to better utilize all illumination entering the tank.

Because a more defined picture could be obtained when the water in the tank was clear, it was necessary to drain the water from the tank at frequent intervals. The centrifugal water pump shown in figure (2) was used to accomplish this. It was necessary to use a polyethylene water bottle to prime the pump.

The three factors contributing to cloudiness in the water were: 1) products of detonation; 2) waste products from low order detonations; 3) white paint from the inside of the tank that was jarred loose by high order detonations. The method used to drain the tank was to stand over the tank with a hose held underwater and pick up each piece of debris. This system required approximately two hours. Because of the long time involved it was found advantageous to clean the tank after several detonations rather than after each one.

Water was maintained at the 30 inch level by using a run-off pipe installed at the correct height. This was connected to a drain in the

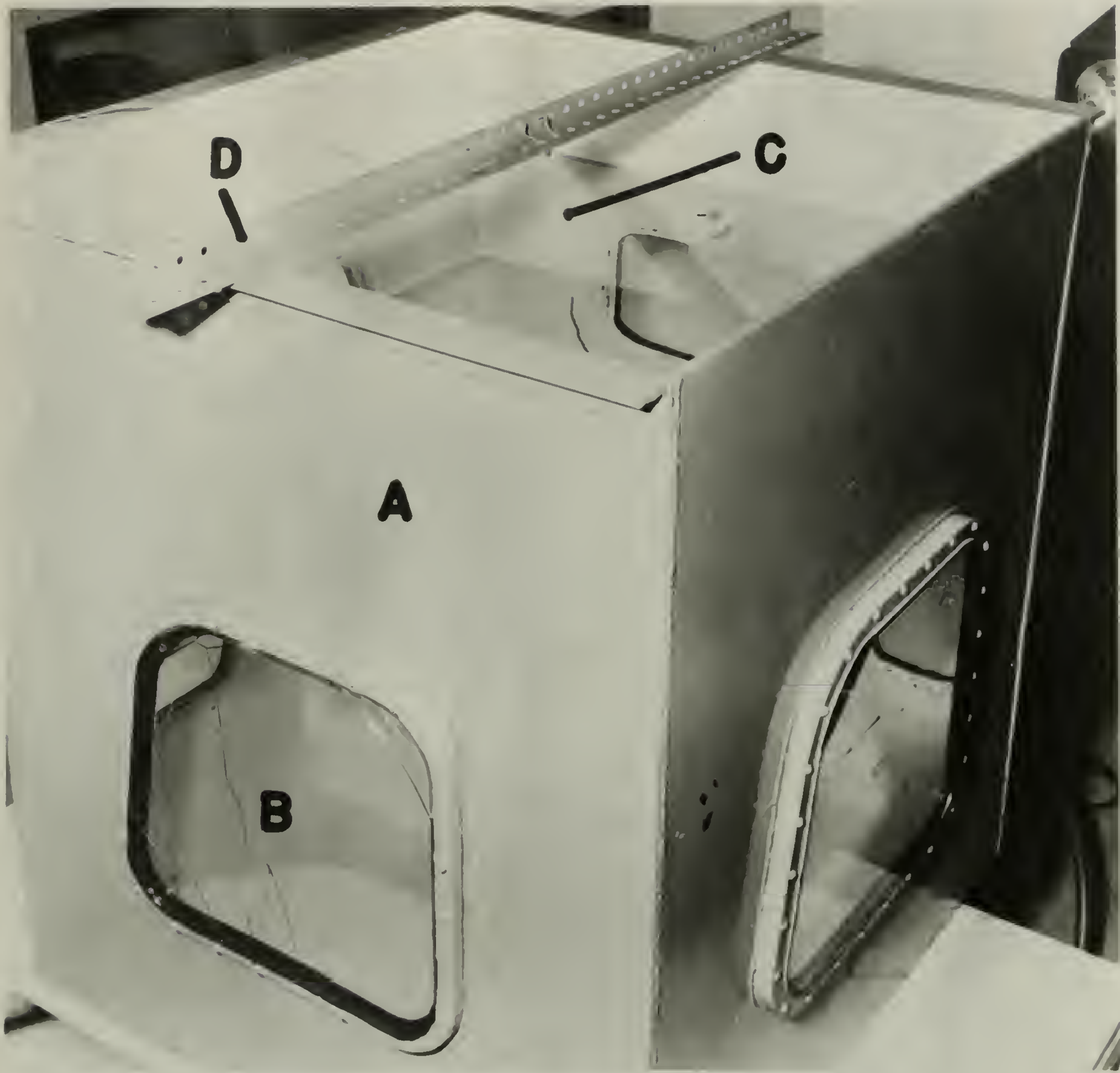

FIG. I

A- TANK

B - FRONT PORT

C- HOOKUP WIRE

D- WIRE SUPPORT BAR

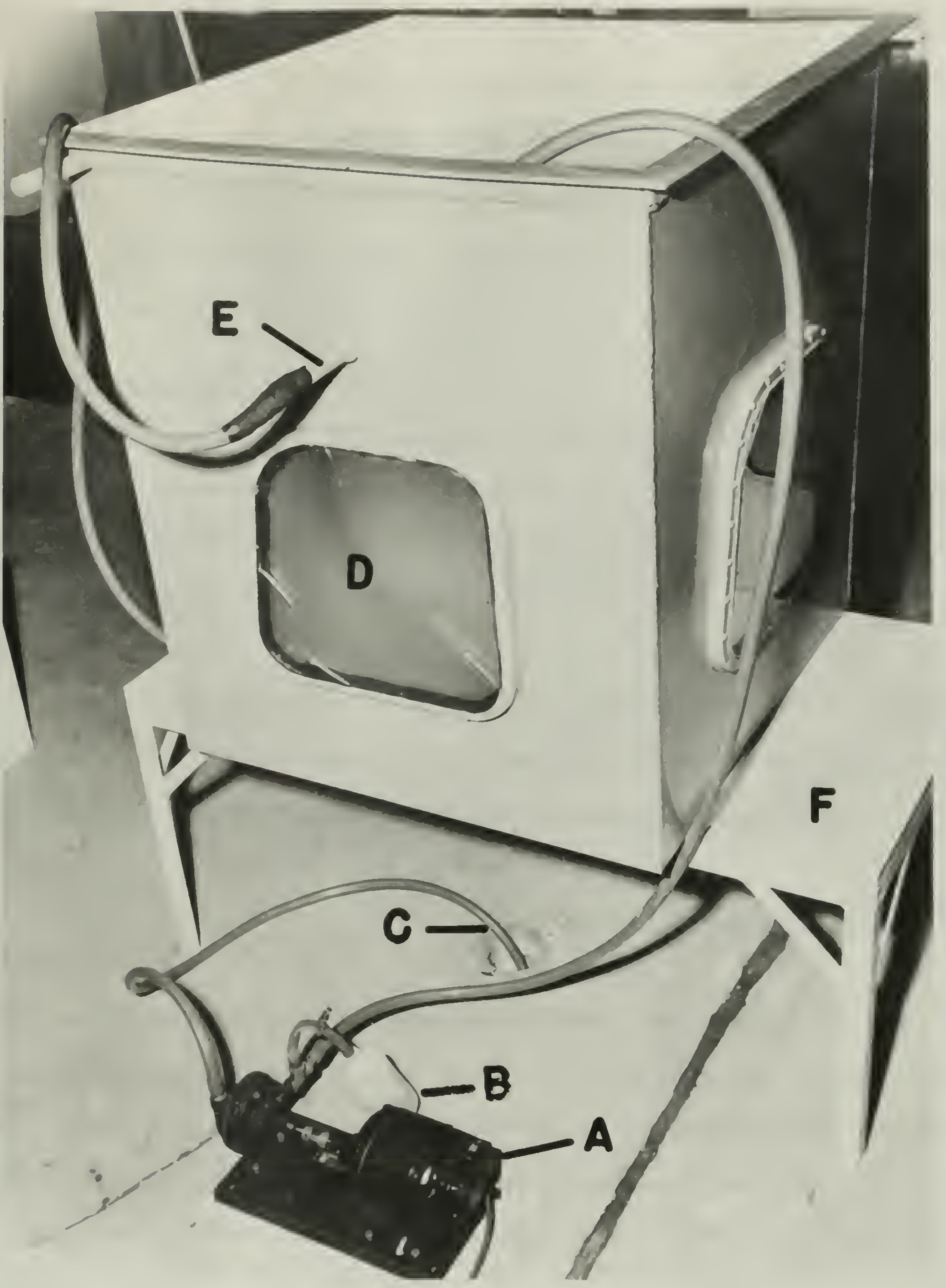

FIG. 2
A- PUMP B- PRIMING BOTTLE
C- DRAIN D- BACK PORT
E- RUN OFF PIPE F- BENCH

floor directly beneath the tank by a rubber hose.

The weight of the tank was approximately 200 pounds. When the tank was filled with water its total weight was over half a ton. Since the tank needed to be raised about 22 inches off the floor to be at the correct height for the camera, a strong metal bench was obtained for the tank to rest on. The bench can be seen in figure (2).

<u>The Firing Circuit</u>.

A 500 microfarad, 200 volt D.C. electrolytic condenser was connected through a switch by Number 18 Hookup Wire directly to the charge. A 150 volt D.C. power supply was connected across the terminals of the condenser to charge it 150 volts. The firing circuit can be seen in figure (3).

The charge was fired by closing the switch which short circuited the condenser through the charge. The maximum energy released by the discharge of the condenser is shown by the following equation:

$$\begin{aligned} E_{max} &= \tfrac{1}{2} C(V)^2 \\ &= \tfrac{1}{2} (500 \times 10^{-6} \text{ farad}) (150 \text{ volt})^2 \\ &= 5.62 \text{ joules} \end{aligned}$$

This was more than enough energy to detonate the charge when the leakage factor of the condenser was as low as 0.3 milliamperes at 150 volts.

Three minutes was ample time to bring the condenser to full charge when the leakage factor was low. The power supply used in the firing circuit was used to accomplish the reforming. This was done by gradually bringing the voltage across the condenser terminals up to 150 volts in 50 volt steps. This could be accomplished in approximately two hours with the power supply connected plus to plus.

The bare charge was attached to the hookup wire by wrapping the fuze wire protruding from the charge around small eyes made in the ends of the hookup wire as shown in figure (4). The charge was then lowered

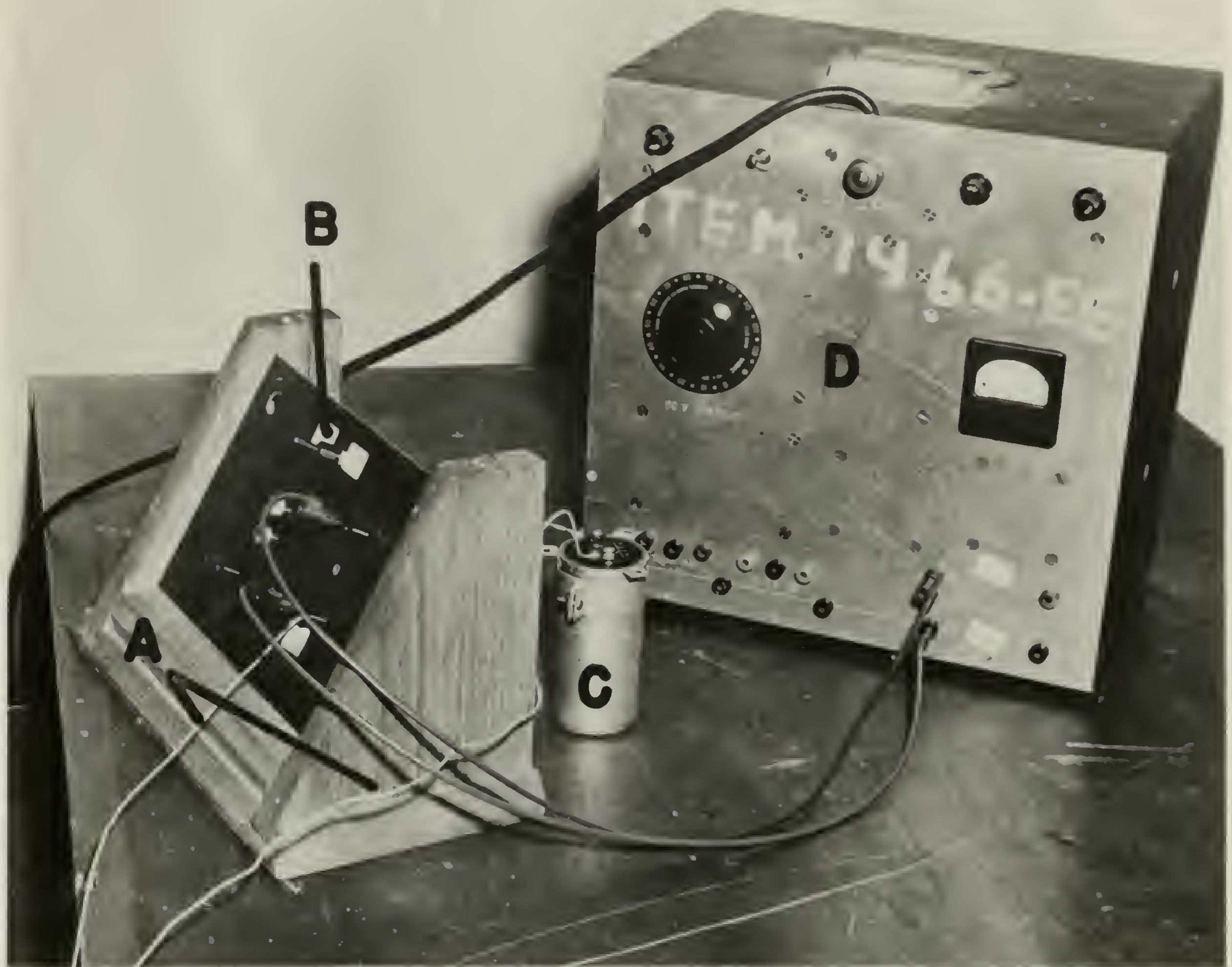

FIG. 3

A- HOOKUP WIRE

B- FIRING SWITCH

C- CONDENSER

D- POWER SUPPLY

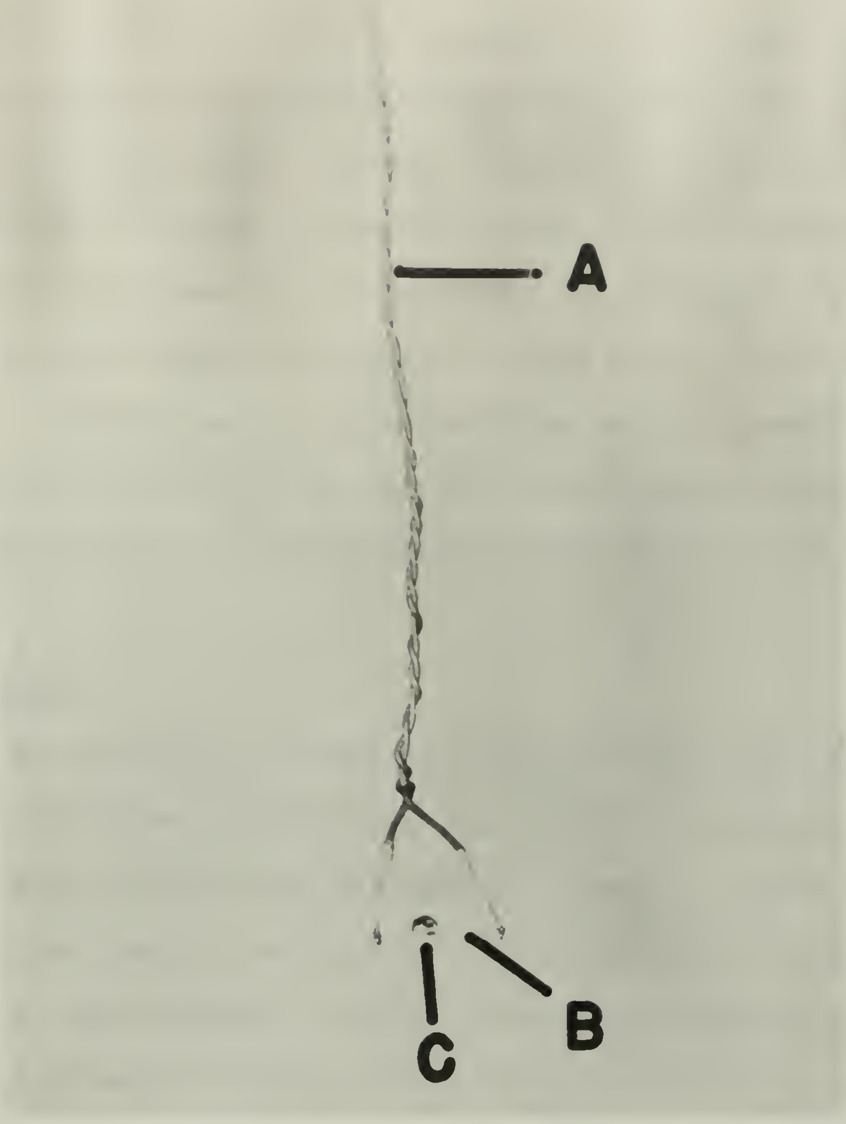

FIG. 4

A- HOOKUP WIRE

B- FUZE WIRE

C- CHARGE

into the water filled explosion tank. The charge was maintained at the standard depth of 15 inches by wrapping the hookup wires around themselves up to the Wire Support Bar directly over the tank. This bar may be seen in figure (1). The added structural strength given the wire was sufficient to keep the charge at the desired depth. During the entire operation of connecting and positioning the charge, safety goggles were worn and the condenser was short circuited across its terminals.

The hookup wire close to the charge was bent upwards by high order detonations, but it was an easy job to bend them back down into position for the next shot. The same pieces of wire were used for the entire project.

Recording.

The recording of bubble pulsations was done with a Wollensak Fastax High-Speed Camera on loan from N.O.T.S. (U.S. Naval Ordnance Test Station, China Lake, California). Operating details of this camera are found in reference (7). This is a 16 mm. high-speed motion picture camera designed to record motion continuity of high-speed subjects ordinarily invisible. It is electrically operated (A.C. or D.C.) and is readily portable. Its maximum framing rate is 7000 frames per second. The camera operates with motion picture film having standard commercial emulsions, but which is especially perforated for the high-speed film drive of the Fastax Camera.

For this project the camera was running at approximately 4000 frames per second. The film used was Eastman Kodak Super-XX Safety Film, Rapid Processing Type 111 Class L with an Exposure Index of 100 and was printed by the facilities at N.O.T.S.. The lens used was a Fastax-Raptor Wollensak two inch (50 mm.) F/2 with aperture wide open

at F-2. The lens-to-charge distance was 6.2 feet.

Due to the high speed of the camera it was necessary to bolt the camera securely to a table to prevent it from moving while running.

In order to get timing marks on the film a 1000-cycle Pulse Generator, again on loan from N.O.T.S., was connected to the built-in neon timing light circuit of the camera. It was from these timing marks that the bubble period was measured.

At the driving voltage used the 100 foot spool of film was run through in 1.2 seconds. This created synchronization problems since the charge was not to be detonated until the camera was up to speed. At first it was thought that a time delay circuit would be necessary to solve the synchronization problem. It was later proved that an operator could guess very effectively at half a second and close the firing circuit after the camera had come up to speed. The latter method was employed in this investigation.

The starting current of the camera was 40 amperes; therefore, it was necessary to use a heavy duty switch and wiring. The camera driving voltage was obtained from a 110 A.C. wall outlet.

The camera with its associated pulse generator can be seen in figure (5).

Illumination.

High-speed photography requires the use of intense illumination to obtain satisfactory results. Since the bubble was viewed by the camera in silhouette against the translucent back port of the explosion tank most of the available lighting was concentrated in this region as can be seen in figure (6).

The three spotlights that were available for this investigation

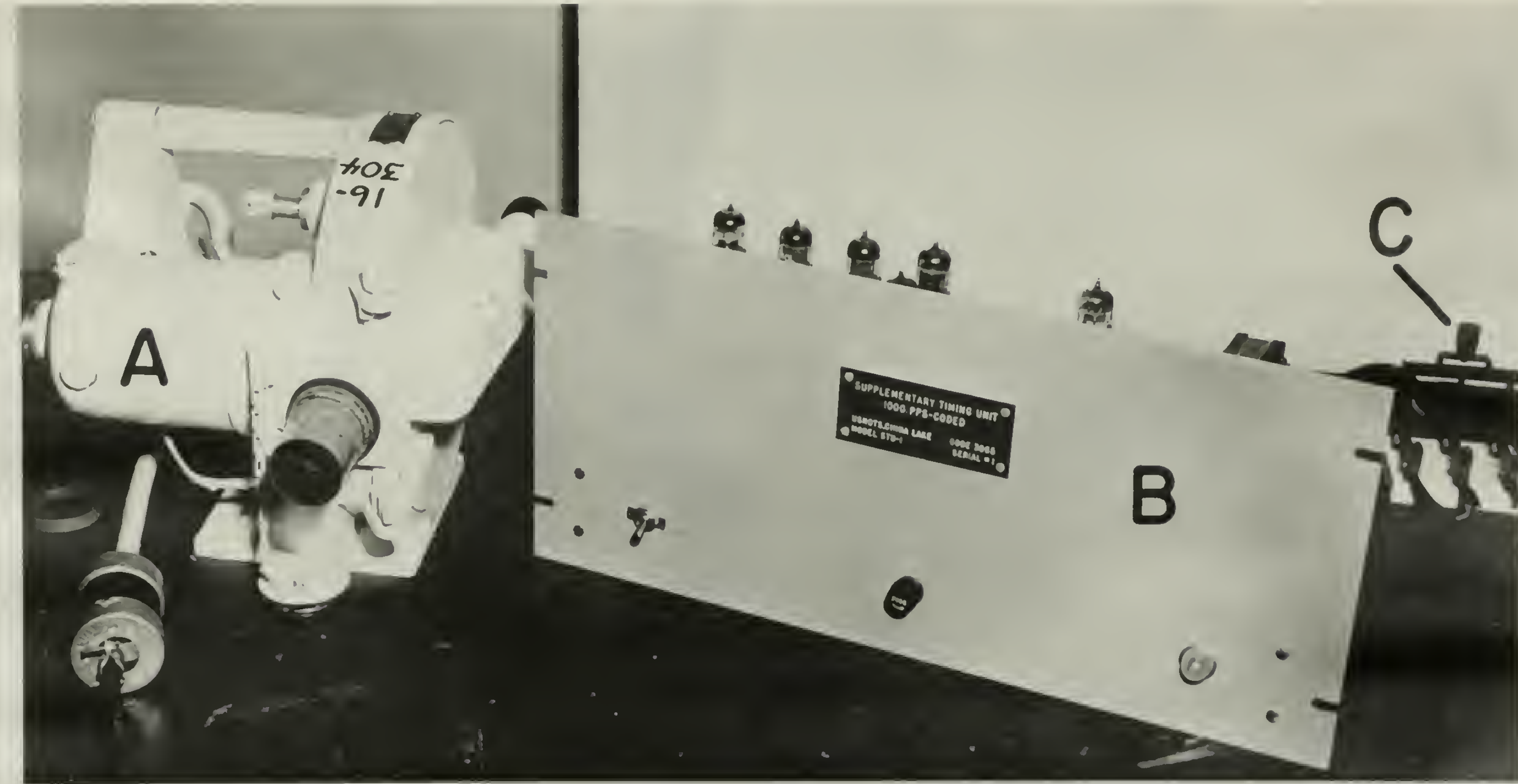

FIG. 5

A- CAMERA B-PULSE GENERATOR

C- CAMERA SWITCH

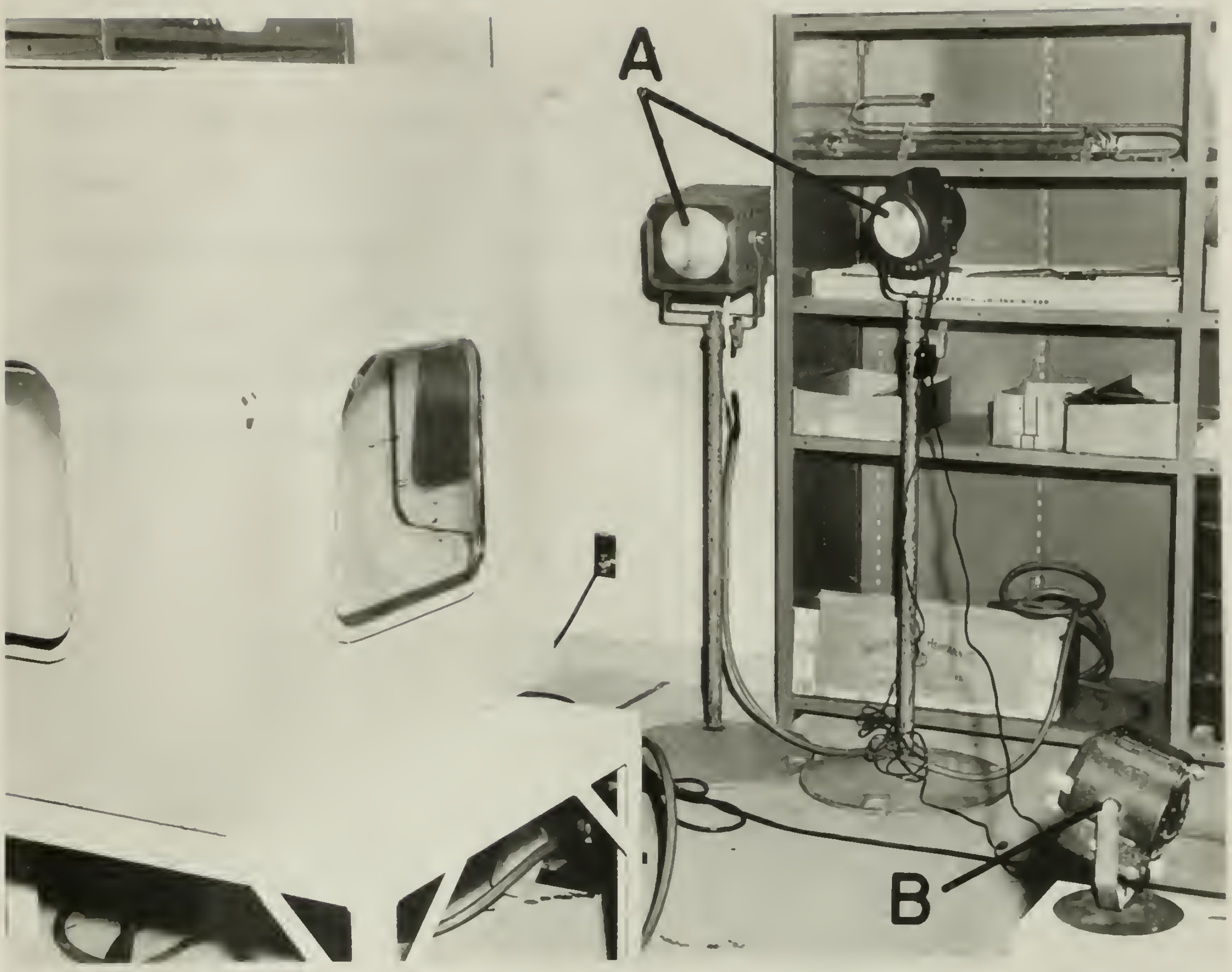

FIG. 6

A- BACK SPOTLIGHTS

B- SIDE SPOTLIGHT

were deployed to put maximum light on the bubble. The translucent back port of the explosion tank was illuminated by two spotlights with a combined power of 800 watts. One side port was illuminated by a 300 watt spotlight. The three spotlights were equipped with bull's-eye lenses so that they could be focused to just cover the ports with light when placed five feet away. Additional lighting was provided by four 200 watt unshielded light bulbs in the ceiling. From personal experience it was found that side lighting gave a three dimensional quality to films of the bubble.

3. Preparation of Charges.

The charges used in this investigation were spherical in shape; however, the first bubble produced by an underwater explosion is spherical regardless of the shape of the detonated charge. Reference (8). A spherical charge was used in preference to another shape primarily because all the equipment and information for making these charges of the desired size was available. The method of preparing the charges was originally designed by Captain P. W. Wilson, U.S.A., and Captain C. J. Treat, U.S.A.. Reference (9). First Lieutenant D. W. Glenn, U.S.A., reference (10), later added many innovations which made the preparation easier.

The method employed was to prepare small detonators directly on short lengths of fuse wire used in Parr Bombs. These detonators consisted of a layer of Lead Styphnate next to the wire with a coating of Lead Azide on the styphnate. P.E.T.N. (Penta-Erythritol Tetranitrate) was then pressed in the form of a sphere around the detonator by the use of a die. Pressure from a hand press on the die was used to give body to the sphere. This was necessary so that the charge could be handled without falling apart. Safety goggles were worn at all times while preparing the charges. The final pressing was done behind safety-plate glass.

P.E.T.N. was chosen as the explosive for the following reasons: 1) it had proved satisfactory in this particular method of preparation; 2) it is commercially available; 3) it is far removed from T.N.T. (Trinitrotoluene) in explosive strength, and since it was to be compared to T.N.T. more conclusive results could be obtained with an explosive far removed from T.N.T. in explosive strength; 4) it is re-

latively non-hygroscopic, reference (11), and since the charge would be underwater when detonated, this was important.

The P.E.T.N. was obtained from the Trojan Powder Company of Allentown, Pennsylvania, and met Military Specifications. Reference (11). The lead azide and lead styphnate were obtained from the Chemistry Division of the Metallurgy and Chemistry Department of the U.S. Naval Postgraduate School.

A 95% confidence interval for the true mean (μ) mass of P.E.T.N. in grams was $0.2298 \leq \mu \leq 0.2376$. The number of charges used was 22 for this calculation; the mean mass of these 22 was 0.2337 grams and the sample variance was 0.008729 grams. The mean mass of the 22 complete charges was 0.2516 grams. These calculations are explained in reference (12). The diameter of the completed charge was 0.706 centimeters giving a press density of 1.36 grams per cubic centimeters.

During the preparation of these charges certain spheres broke in half causing hemispherical charges. A few of these hemispheres were detonated for comparative purposes. The average mass of these was 0.1485 grams with the P.E.T.N. weighing 0.1306 grams. These hemispheres had the same density since they broke in the final step of preparation.

4. Data.

The experimental data taken from the developed film is included as Table 1. This data includes the first and second bubble periods of the spherical charges, plus the ratio of the second to the first. These times could be read accurately to within 0.1 millisecond. Table 2 contains similar data for hemispherical charges.

Table 1

Shot Number	T_1(milliseconds)	T_2(milliseconds)	T_2/T_1
1	17.1	11.2	0.66
2	18.0	11.1	0.62
6	16.8	11.2	0.67
8	17.0	11.2	0.66
9	16.9	11.0	0.65
10	16.8	11.2	0.67
11	16.8	11.1	0.66
12	17.2	11.1	0.64
13	16.7	11.4	0.68
15	17.2	11.0	0.64
16	16.9	11.0	0.65
17	17.0	11.3	0.66
18	16.6	11.1	0.67
19	16.6	11.3	0.68
Average Value	17.0	11.2	0.66

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[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]

Table 2

Shot Number	T_1(milliseconds)	T_2(milliseconds)	T_1/T_2
3	15.4	11.0	0.71
4	16.0	10.9	0.68
5	15.0	10.9	0.73
7	14.7	11.0	0.75
14	14.7	10.7	0.73
Average Value	15.2	10.9	0.72

5. Computational Procedure.

Computations were made to arrive at a figure for the relative underwater explosive strength of P.E.T.N. and T.N.T.. The semi-empirical formula with a rational basis used for the bubble period of T.N.T. was taken from reference (1).

$$T_n = 0.561 \frac{(r_n Q W)^{1/3}}{Z_n^{5/6}}$$

With the subscript n standing for the nth bubble period. T_n is in seconds, Z_n is in feet of water used, W in grams, Q is kilocalories per gram, and r_n is the fraction of the detonation energy Q which remains for the nth oscillation of period T_n. The constant 0.561 was verified by experiment on T.N.T. ranging in mass from detonators to 300 pounds and in depth from 3 feet to 700 feet. The average of the experimental first bubble period for P.E.T.N. and the actual hydrostatic pressure on the charge (Z_1 = 35.45 feet of fresh water) were substituted for the factors T_n and Z_n. The mass of T.N.T. that would have produced this bubble period at this pressure was then calculated. This mass of T.N.T. was compared to the actual mass of P.E.T.N. used. This comparison gave the relative underwater explosive strength of P.E.T.N. and T.N.T.. The calculation was used on data from hemispherical as well as spherical charges.

From the spherical data the 0.2337 grams of P.E.T.N. used was equivalent to 0.310 grams of T.N.T., or P.E.T.N. had 1.33 times the underwater explosive strength of T.N.T. when measured by this method. The data from the hemispherical charges showed that the 0.1306 grams of P.E.T.N. used was equivalent to 0.222 grams of T.N.T. or P.E.T.N. had 1.70 times the underwater explosive strength of T.N.T..

The explosive strength of the small lead styphnate - lead azide detonators used in the explosive train was neglected in the calculations. Photographic investigation confirmed that these added too small a contribution to be considered.

6. Conclusions.

Figures (7) through (29) show that it is possible to obtain clear, well defined high speed motion pictures of bubbles from laboratory scale underwater explosions. These figures further reveal that the dimensions of the explosive tank were correct for the mass of explosive used so that the corrections discussed in reference (13) due to proximity of surrounding surface and gravity could be neglected for the first bubble period. This was not true for subsequent pulsations as these photographs show.

The millisecond timing marks on the film gave a simple method of obtaining bubble period data. From these data the relative underwater strength of P.E.T.N. could easily be obtained. The figure for the relative underwater explosive strength of P.E.T.N. is not in the literature, but the figure of 1.33 times the underwater explosive strength of T.N.T. does fit in rather well with data that is in the literature for other explosives. Reference (1). This investigation as well as a literature search showed that the explosive strength of explosives in water is not the same as it is in air, and that the water value is the lower of the two. A possible explanation for this difference could be the greater cooling effect of water compared to air.

The miniaturization technique developed for comparing the underwater explosive strength of P.E.T.N. and T.N.T. can be adapted to other explosives. Just as in air, more quanitative results can be obtained when explosive strengths are obtained from the same machine under identical conditions.

APPENDIX I

Figures (7) through (29) show the entire sequence of events of an underwater explosion from detonation to the collapse of the second bubble. Shot number 15 was chosen to represent the results of the photographic investigation. The timing marks on the side of the film are easily recognizable.

FIG. 7

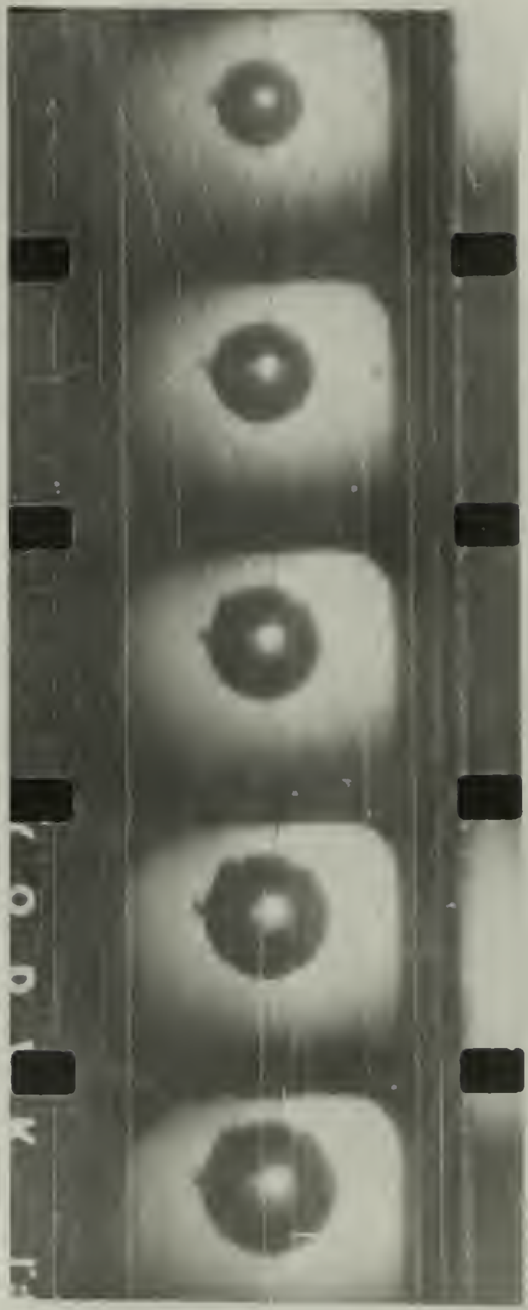

FIG. 8

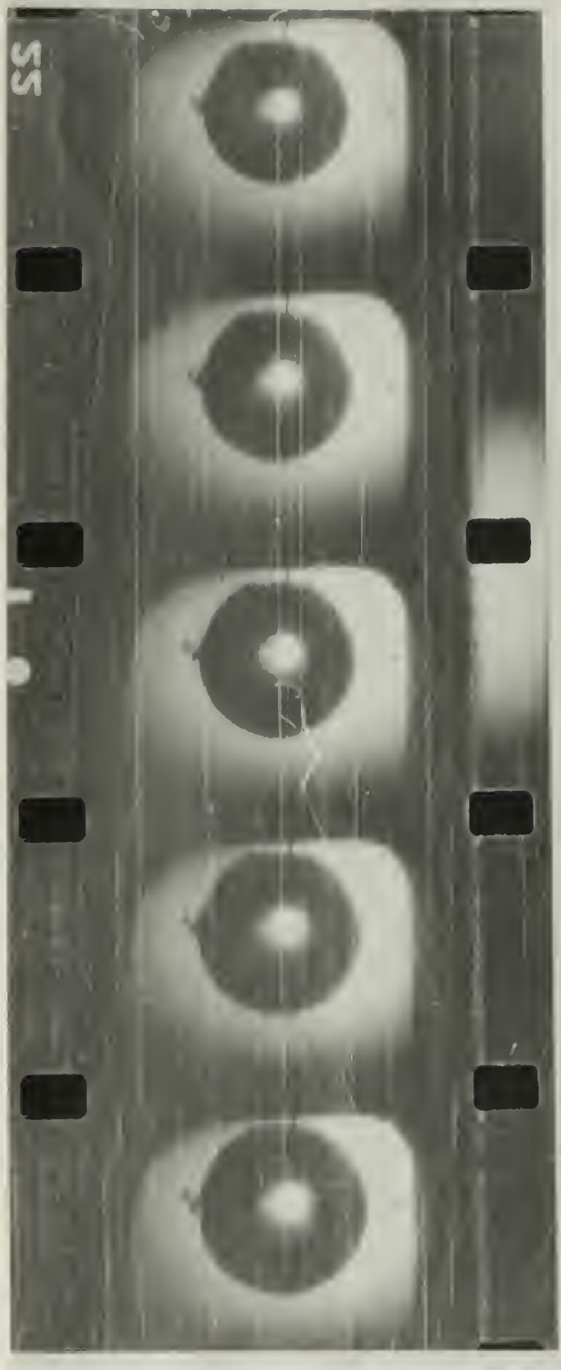

FIG. 9

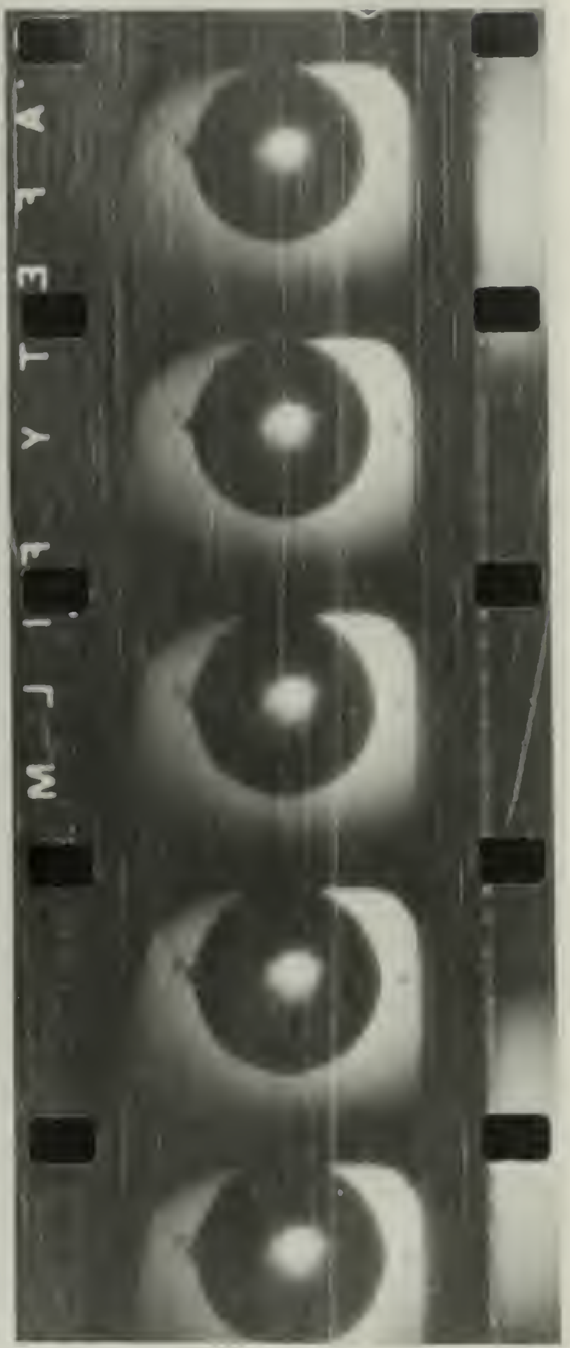

FIG. 10

FIG. 11

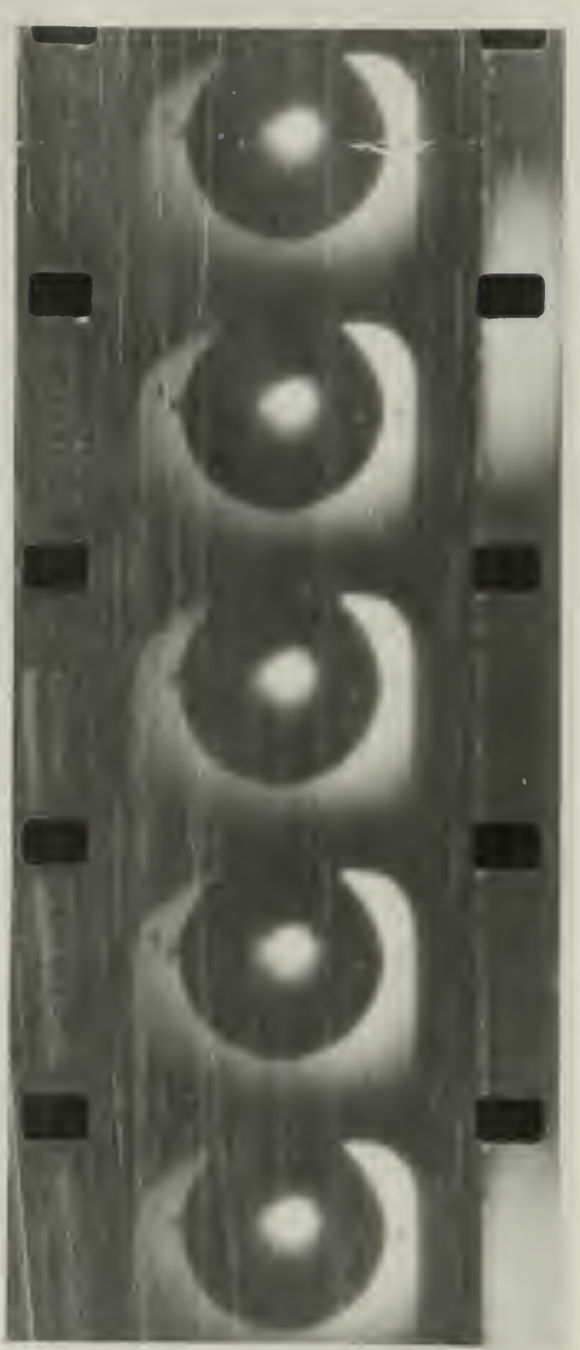

FIG. 12

FIG. 13

FIG. 14

FIG. 15

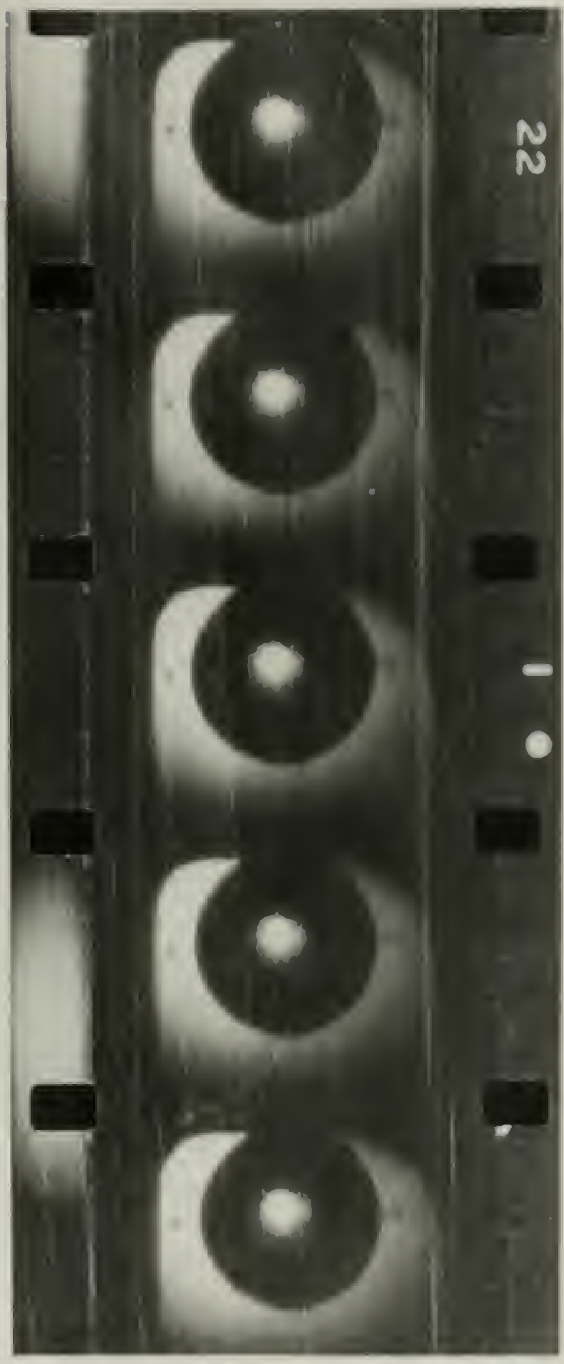

FIG. 16

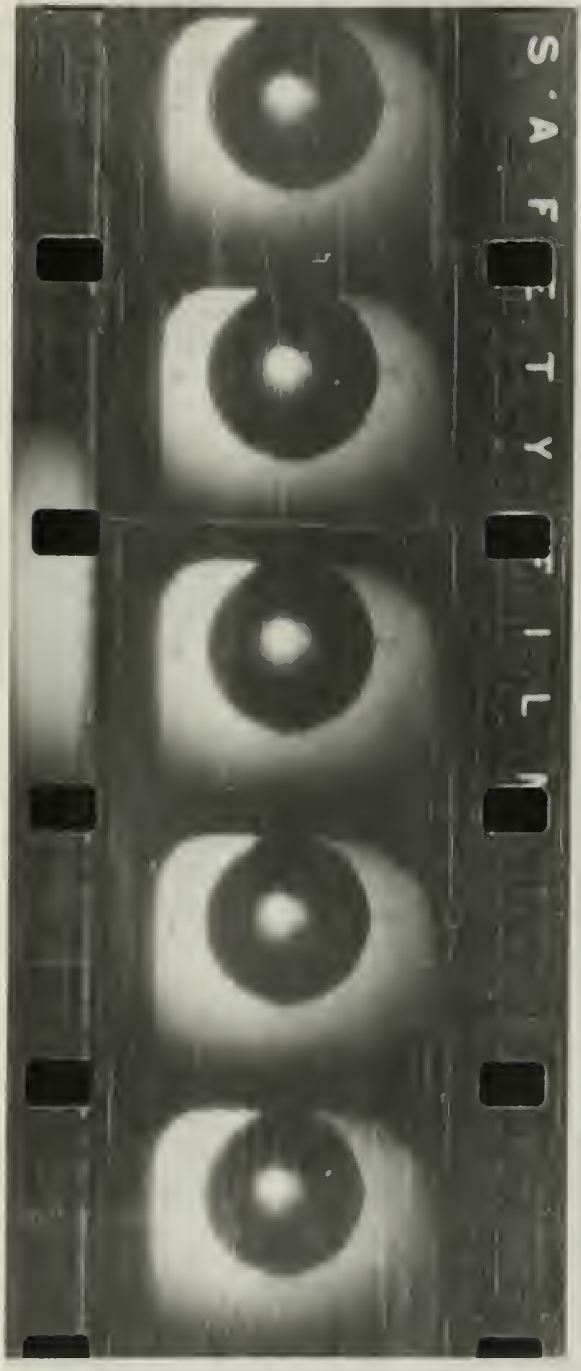

FIG. 17

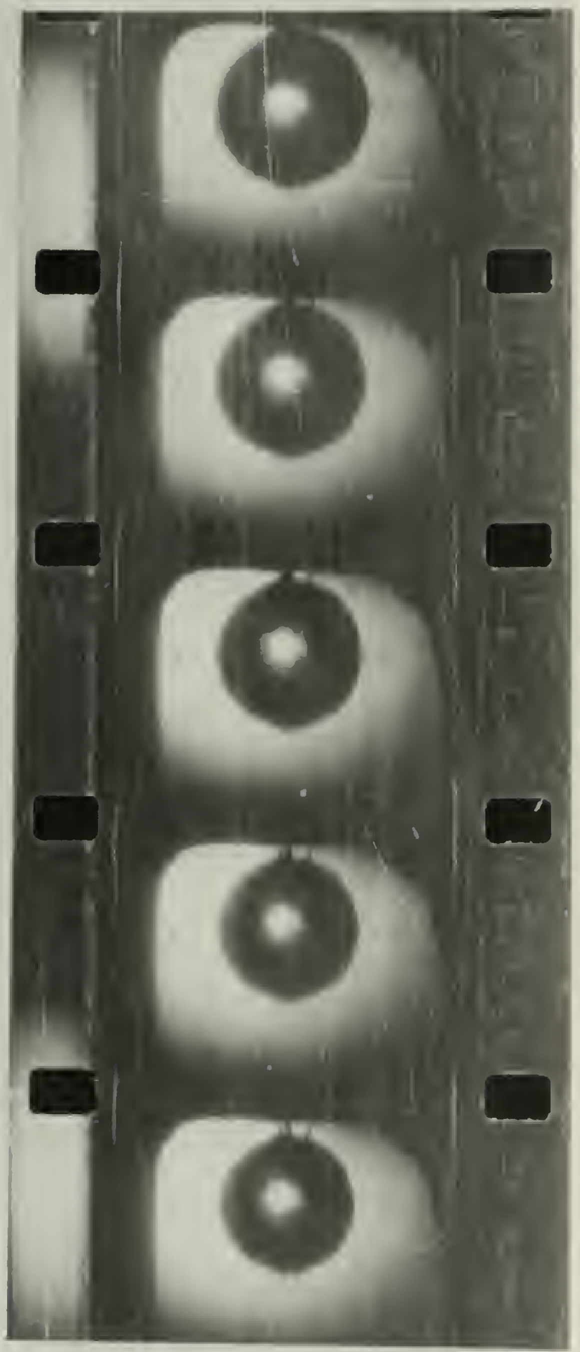

FIG. 18

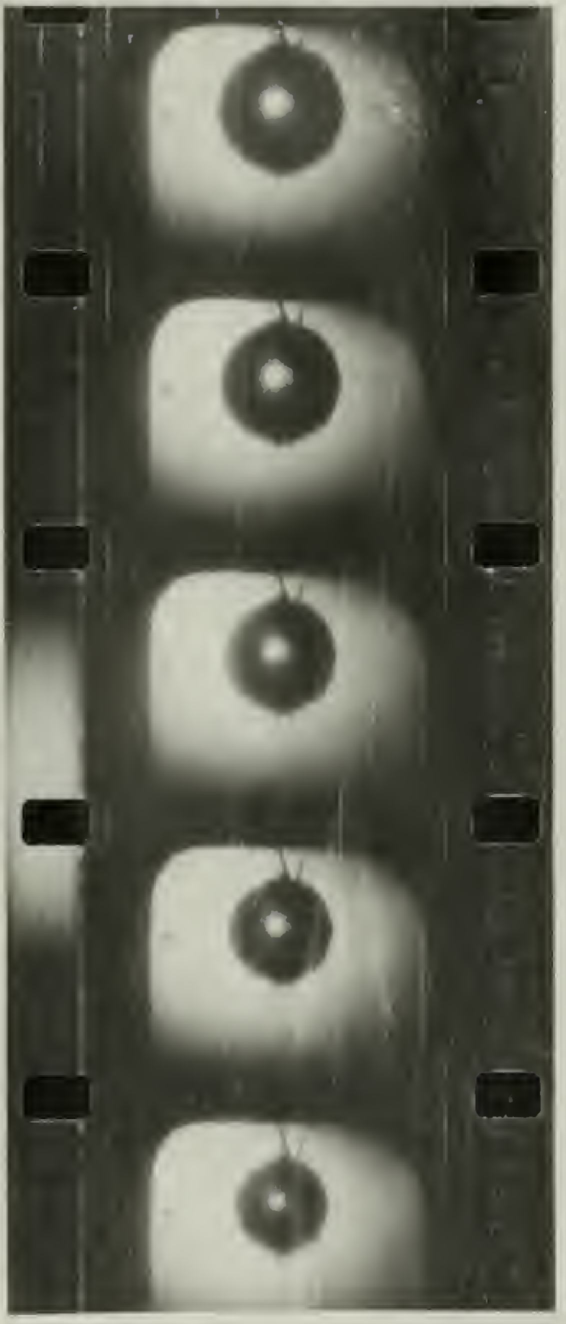

FIG. 19

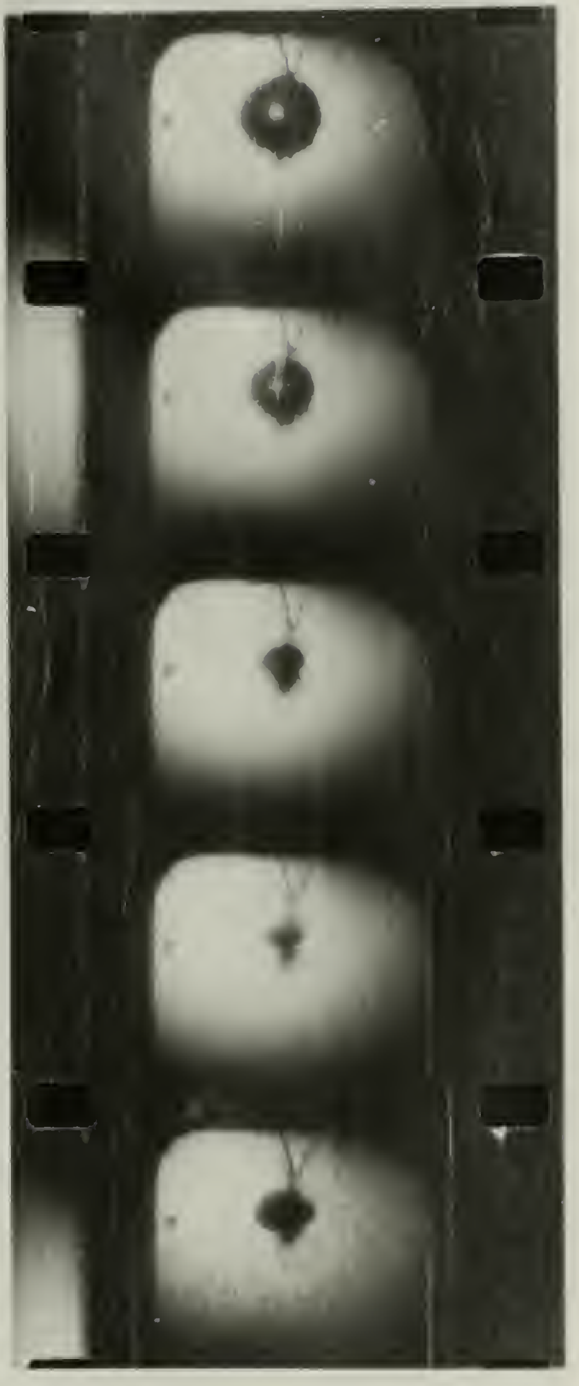

FIG. 20

FIG. 21

FIG. 22

FIG. 23

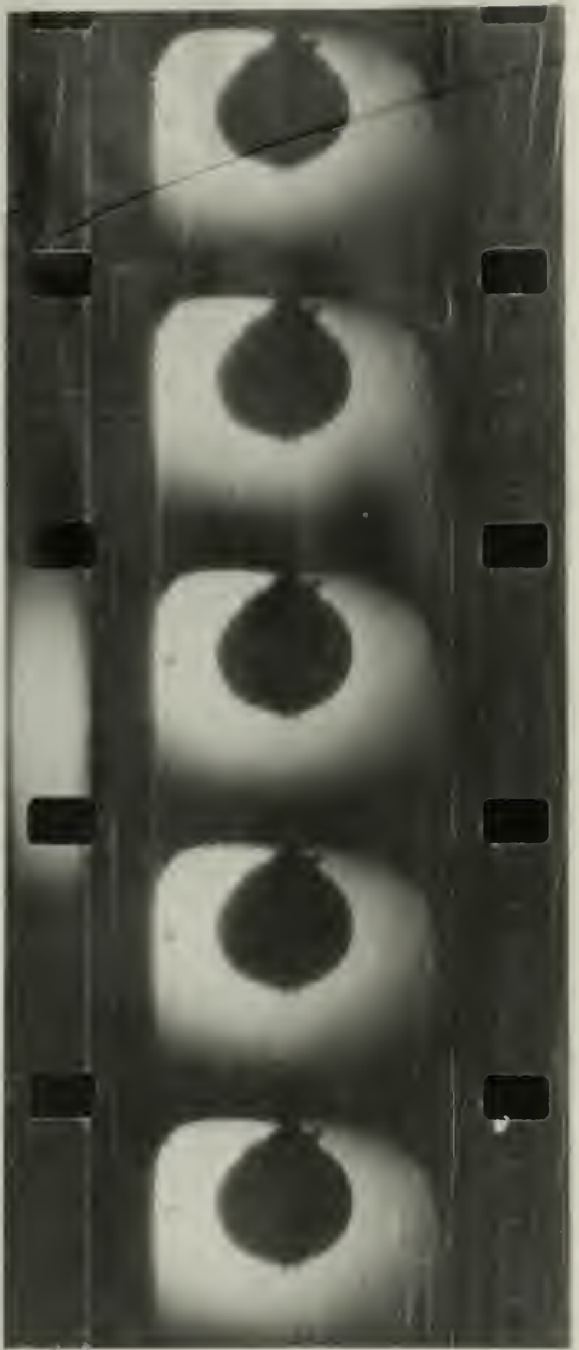

FIG. 24

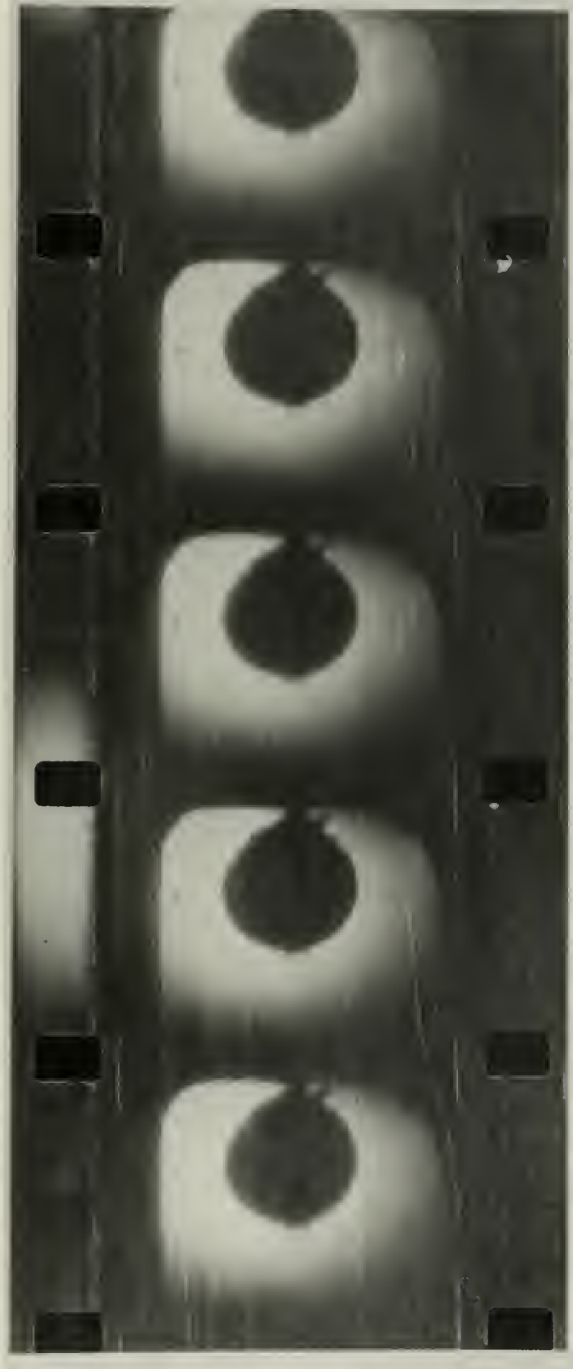

FIG. 25

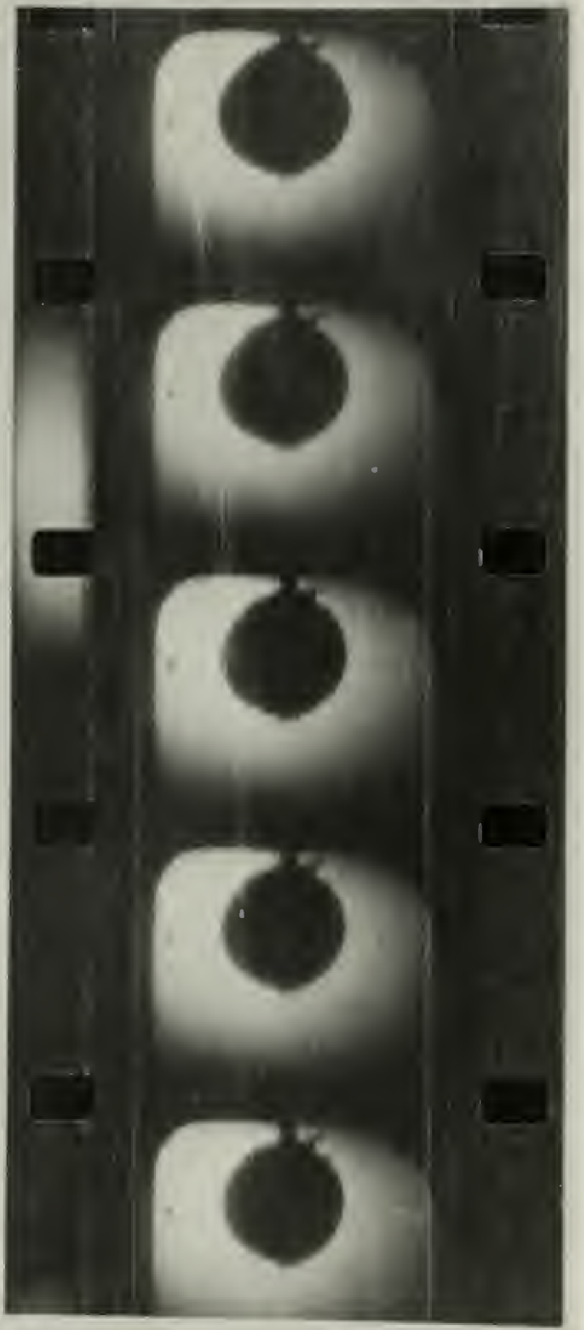

FIG. 26

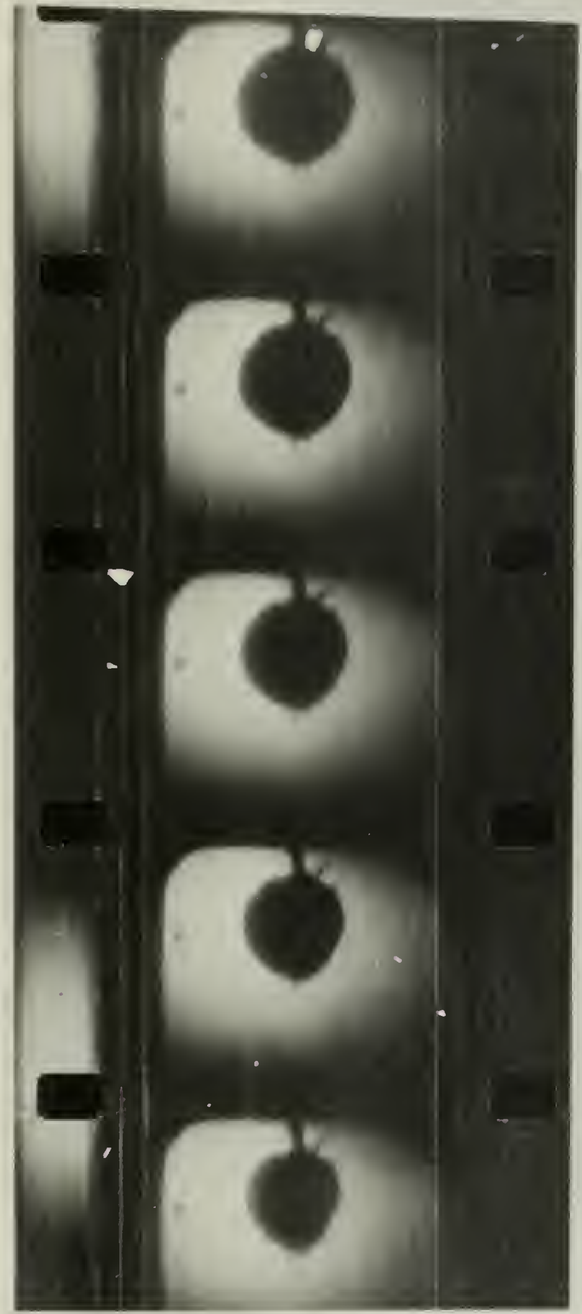

FIG. 27

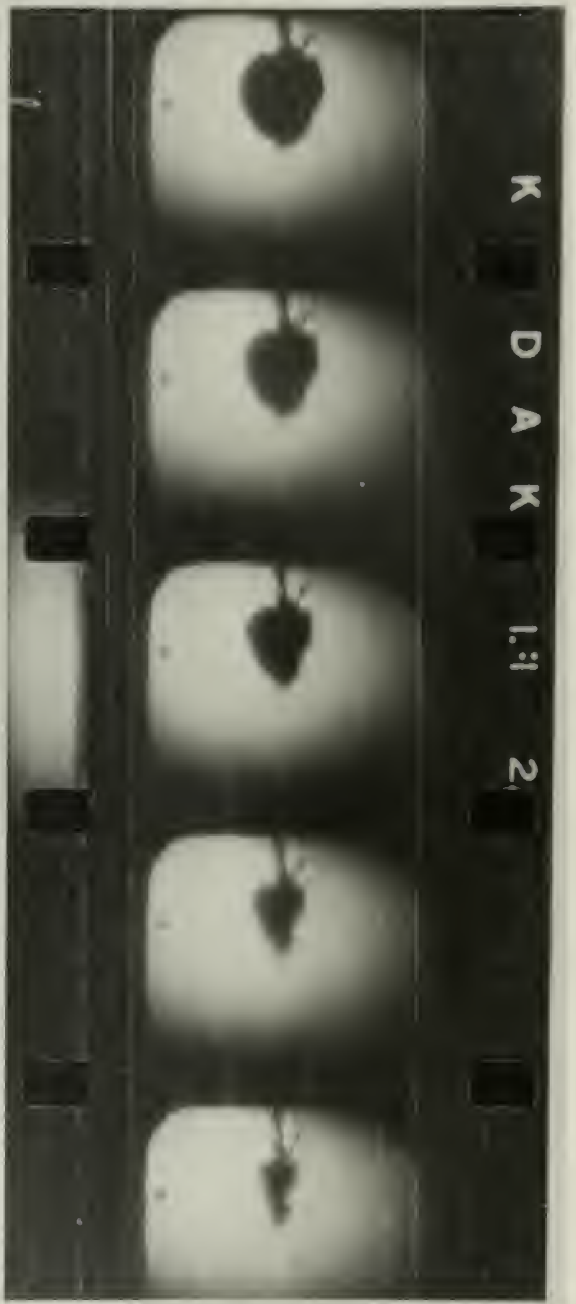

FIG. 28

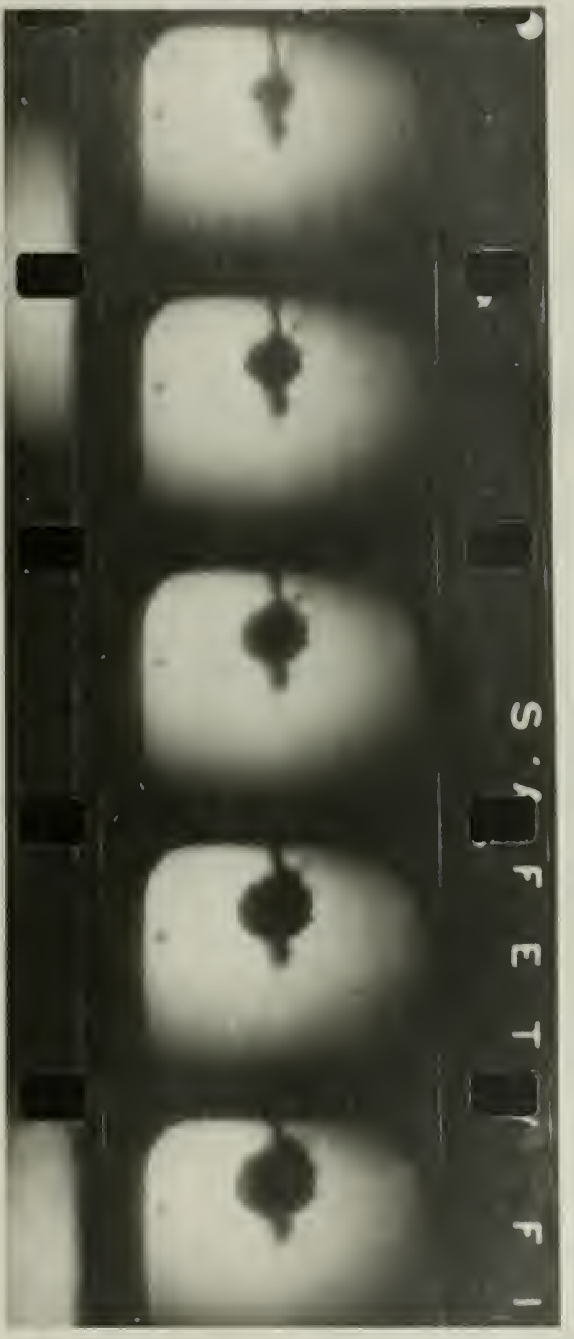

FIG. 29

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